Reliability and Bifurcation in Neurons Driven by Multiple Sinusoids

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Introduction

Varying the amplitude and frequency of a sinusoidal current injection can modulate the reliability and precision of neuronal discharge.

The response of a neuron driven with multiple frequency components cannot be wholly predicted from the responses to single sinusoids.

We study the dependence of spike-time reliability on:
1. The relative phase of two frequency components.
2. The choice of the second (higher) frequency.
3. The distribution of power between two frequency components.

Methods

Stimuli: We injected cells with currents of the form:

I(t) = A0 + A1 sin(w1 t) + A2 sin(w2 t + phi).

Experiment 1: The phase offset phi varied from 0 to 2 pi, keeping w1 = 5Hz and w2 = 10 Hz and A1=A2=50 pA and A0 = 100 pA.

Experiment 2: The second frequency w2 varied from 10 Hz to 105 Hz in increments of 5 Hz, commensurate with the slow frequency (w1 = 5 Hz). We kept A1=A2=12.5 pA and A0=50 pA.

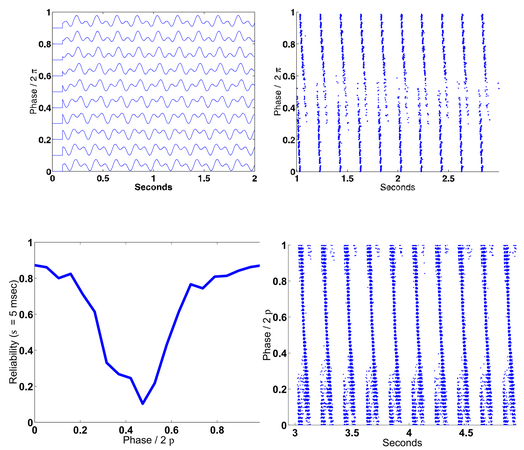
Experiment 3: The amplitudes A1 and A2 varied while their total power (A1 ^2 + A2 ^2) ^ (1/2) remained fixed at 15 pA. We kept A0 = 50 pA, w1 = 5 Hz and w2 = 35 Hz.

In vitro: We used layer V prefrontal cortex pyramidal cells in 2-3 weeks old Sprague Dawley rats. Whole cell patch technique at 31 ℃. Synaptic transmission was blocked with DNQX (10 M), APV (50 M), Biccuculine (20 M). All drugs were bath applied.

Simulations: We performed simulations with the integrate-and-fire neuron model: dv/dt = -v/tau + I(t) with v(t) reset to 0 upon reaching threshold at v = 1. We solved the integrate-and-fire equation numerically using 4th-order Runge Kutta (Press et al, Numerical Recipies in C.)

Analysis of Reliability: We used the correlation measure of reliability introduced by Schreiber *et al* (see Schreiber *et al* poster, this session). In brief, we convolved spike trains with a Gaussian filter of standard deviation sigma, and calculated the normalized inner product between each pair of the smoothed responses to a given stimulus. On a time-scale given by sigma, the measure reports the correlation of firing times ranging from 0 (uncorrelated, poor reliability) to 1 (complete reliability).

1 . Varying relative phase.



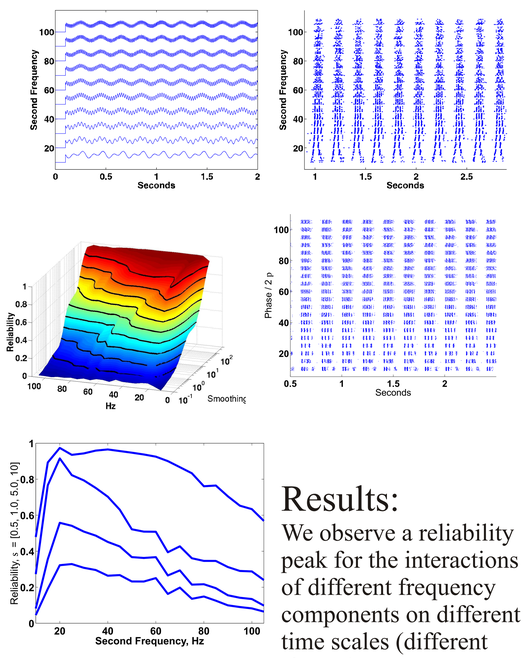
Results

Varying the relative phase offset changed the response from highly reliable to highly unreliable (sigma = 5 msec). The reliability minimum occurs at a spike-timing bifurcation, due to the coexistence of two spike-timing attractors.

Significance

Makeig et al observed a rapid shift in relative phase of two frequencies in human EEG following stimulus onset. Shifting phase (without shifting power) could rapidly change firing-pattern reliability, creating or removing correlated activity and altering the gain in the affected pathway.

2 . Varying the "gamma" frequency.



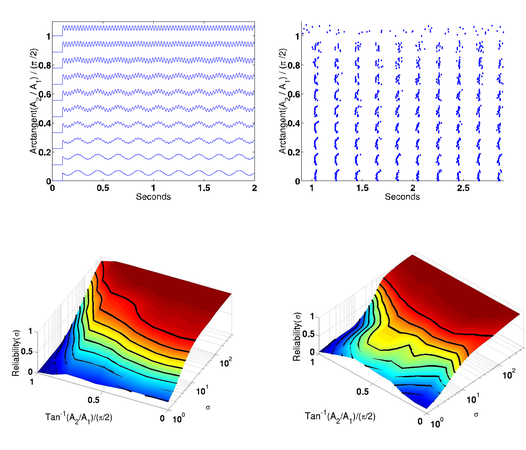
Results:

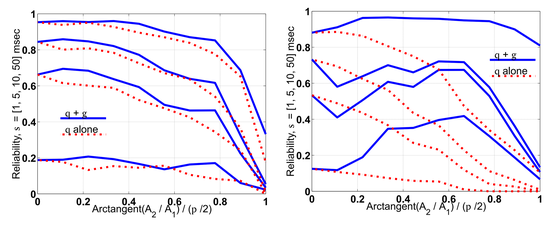
We observe a reliability peak for the interactions of different frequency components on different time scales (different sigmas).
On a fast (1-5 msec) timescale the interaction of 5 Hz and 20 Hz gives the most reliable firing.
On a slower (>10 msec) time scale the interaction of 5 Hz gives two reliability peaks:
one at 20 Hz and another at 40-50 Hz.
Firing times show both theta-scale and gamma-scale precision for gamma frequencies < 50 Hz.

Significance:

Nowak et al showed adding gamma-power to a theta rhythm could increase spike-time precision, possibly enhancing neural encoding. The optimal "gamma" frequency for enhancing reliability and precision depends both on the noise of the neural dynamics and on the decoding time scale.

3 . Varying the balance of power.





Results:

Shifting power from the theta component to the gamma component *can either increase or decrease reliability*. Cells with precise locking to pure theta show enhanced reliability when some power shifts to gamma. Cells with less precise locking to pure theta undergo a spike-timing bifurcation to two+ different gamma-cycles, reducing reliability.

Significance:

Fries et al observed a shift between theta-band and gamma-band coherence during attentional modulation of local field activity. A precision-threshold for reliability could enhance correlation-based modulation of information flow in cortical networks..

Conclusions

Nonlinear superposition:
Combining two frequencies in a neuron's input leads to novel effects, including:
Relative Phase
There are optimum phases for peak reliability and unreliability, respectively.
Choice of Gamma
The optimum gamma-frequency depends on the decoding time scale and internal noise.
Power Balance
Shifting power from theta to gamma frequencies can either increase or decrease reliability.

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